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**Analysis of the effects of sire and age on wool quality traits in
Romney ewes**

A Dissertation
submitted in partial fulfilment
of the requirements for the Degree of
Bachelor of Agricultural Science (Honours)

at
Lincoln University
by
Hamish Jackson Holloway

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Higher prices for sheep meat compared to strong wool have caused dual purpose sheep breeding objectives to align with meat production. The resulting lack of focus on wool breeding has resulted in reduction of the quality and value of strong wool. This dissertation examines the results of a wool breeding trial being conducted with Romney ewes in North Canterbury, New Zealand. Wool trait data collected from the first generation progeny was analysed. The trial aims to increase the value of Romney wool by improving its quality. Key wool traits which affect processing performance and end-use were assessed using the Fibrescan objective wool measurement system. Wool staples were side-sampled from each of 437 ewes as hoggets and again as two tooth. Sampling date significantly affected mean fibre diameter (MFD), mean curvature, coarse edge (% fleece $10\mu > \bar{x}$) and the proportion of ewes with wool medullation ($p < 0.001$). Average changes in wool traits between hoggets and two tooth were as follows. MFD increased 5.5 micron (hogget $\bar{x}=31.9$, two tooth $\bar{x}=37.4$). Mean curvature decreased $15.2^\circ/\text{mm}$ (hogget $\bar{x}=71.3$, two tooth $\bar{x}=56.1$). Coarse edge increased 1.8% (hogget $\bar{x}=8.8\%$, two tooth $\bar{x}=10.5\%$). The proportion of ewes with medullation decreased (hogget $\bar{x}=13.7\%$, two tooth $\bar{x}=6.4\%$). Sire was recorded for 181 ewes, which allowed the performance of sires to be compared for each wool trait. Sire significantly affected MFD, staple length, mean curvature, and coarse edge ($p < 0.001$), as well as the coefficient of variation of MFD (CVMFD) ($p=0.004$). The results agree with previous findings in the literature. The changes in wool traits between hoggets and two tooth have implications for accurately selecting replacement and cull animals in a wool breeding program. The difference in wool traits between sires indicated that these traits can be improved via selective breeding.

Keywords: mean fibre diameter, MFD, mean curvature, fibre curvature, crimp, medullation, coarse edge, staple length, wool value, selective breeding.

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Chapter 1

Introduction

Historically, sheep farming was New Zealand's agricultural backbone, and despite recent declines in total sheep numbers, it is still a major contributor to the country's primary industries. There were 27.6 million sheep in 2016, down from a high of 70.3 million in 1982 (Stats NZ, 2016). Relative to total export prices, wool prices dropped 42% from their high in 1989 to 2011 (Stats NZ, 2011). New Zealand was the third largest producer of wool in 2015-2016, accounting for 9.5% of world production (Beef and Lamb NZ, 2017). Cottle (2010) noted that most industries go through life cycles, and that failure to innovate results in commoditization and subsequently a decline. Alternatively, innovation, market anticipation and the creation of greater value market segments typically result in a second phase, whilst solely increasing volume of product sold often does not. This forces consideration of whether New Zealand's wool industry is poisoning itself for a second life, or whether it will remain in decline.

The majority of New Zealand's sheep industry is based on dual-purpose breeds producing lambs for meat, as well as medium-coarse wool. These products are mainly sold as undifferentiated commodities to processing companies (Simm, 1998). Currently, lambs are the main source of revenue for sheep farmers (Beef and Lamb NZ, 2017). Better prices for lamb compared to wool have resulted in breeding programs improving lamb production traits faster than wool production traits (Craven et al, 2009).

Table 1 Typical mean fibre diameter of wool of different categories, examples of the major breeds which produce each wool type, and end-uses of the wool (Simm, 1998).

Wool category	Fibre diameter (microns)	Example breeds	End-use of wool
Fine	Up to 25 μ	Merino, Polwarth	Light weight, high quality clothing and knitwear
Medium	25 to 30 μ	Corriedale, Merino cross-breds	Medium weight clothing. Machine and hand knitted yarns.
Coarse	30 μ and over	Romney, Coopworth, Perendale	Heavy weight clothing. Blankets. Furnishing fabric. Carpets.
Speciality carpet	Medullated, mean 40 μ	Drysdale, Tukidale, Carpetmaster	Carpets. Upholstery fillers.

Wool is used primarily for the production of garments, furnishings, fillings and carpets. The two strongest determinants of end-use are mean fibre diameter (MFD) and staple length. Table 1 summarises the typical MFD and end-uses of the wool of different breeds.

The importance of MFD is based firstly on it being the dominant characteristic affecting all stages of the processing chain. Further importance stems from its effect on textile weight and comfort. Finer fibres produce lighter textiles, and are more comfortable to wear next to the skin (Simm, 1998). This in turn allows them to be incorporated into higher value end-uses, which is reflected in the price paid for raw wool (figure 1). Consequently, wool may contribute 80% of a Merino farmer's income, but only 10-30% of a lamb producer's income (Piper et al, 1997).

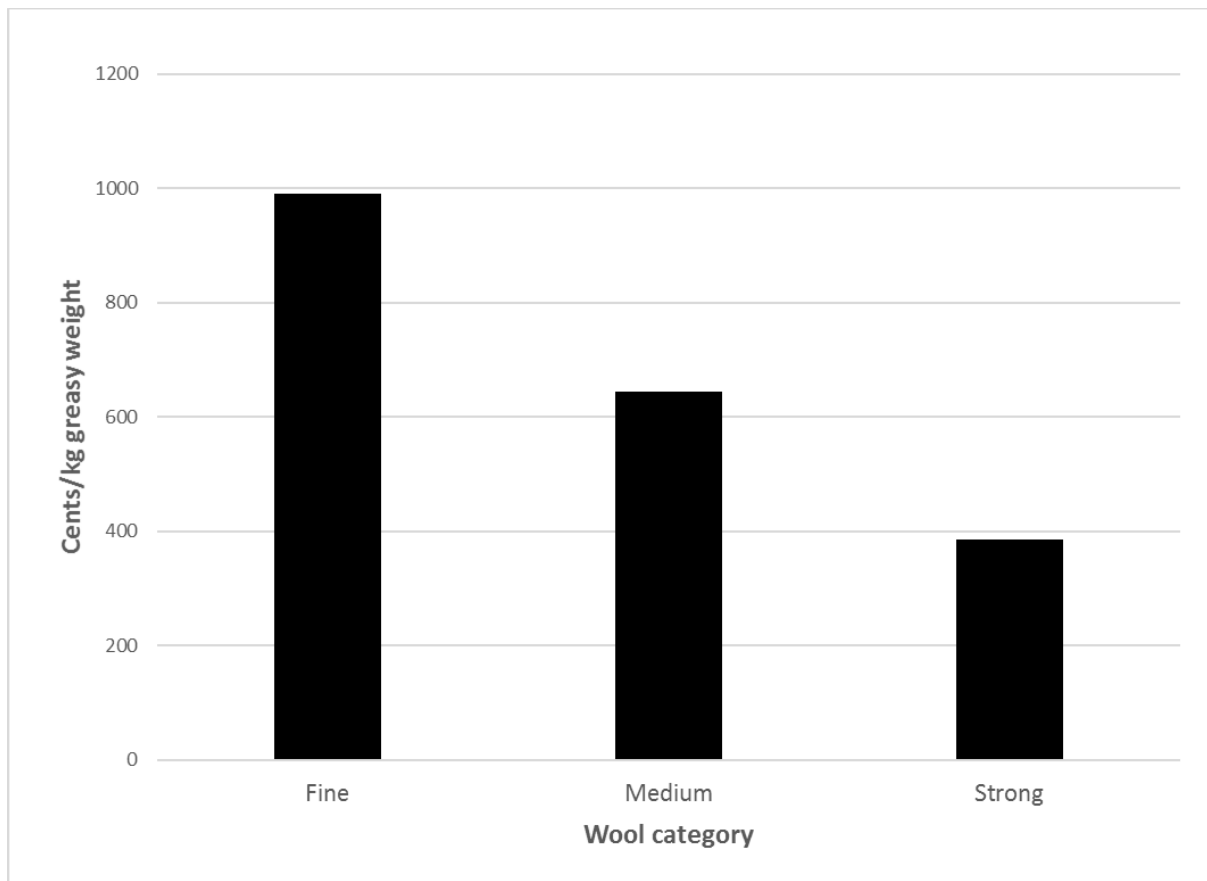


Figure 1 Average prices (2014-17) for wool fibre diameter categories. Adapted from Beef and Lamb NZ (2016).

The comparative importance of Merino producers to the wool industry means that they have received most of the genetic research focus. Nonetheless, the principles are the same across breeds. Genetic improvement of raw wool is focused on:

- increasing fibre production to give a greater economic return per hectare, and/or
- improving fibre quality to allow it to be incorporated into superior end-uses, thus increasing the per unit value of the wool (Piper et al, 1997).

In this context, the second area is the most pertinent. The development of an efficient breeding program to achieve the goal then relies on:

- identification of appropriate traits for improvement, followed by attaching relative economic values to determine the emphasis on each trait.
- a precise understanding of the heritabilities and correlations of the traits, so that an effective prediction of response to selection can be made (Piper et al, 1997).

The improvement of wool traits has its foundation in on-farm recording. The employment of an objective system of wool assessment allows the prediction of processing performance and final

product quality from the raw wool (Rogan, 1988). By predicting processing performance, wools of a similar quality can be baled together and sold as a differentiated product. This allows wool mills to select their raw wool based on their desired characteristics (Cottle, 2010).

This dissertation examines the results of a wool breeding trial currently being conducted on 'The Doone', a property running sheep under extensive conditions in North Canterbury, New Zealand. The primary objective of this trial is to increase the value of the flock's wool clip via selective breeding. This research provides information on the viability of on-farm selective breeding for market-desired wool traits.

The objective of this study was to determine the effects of sire and age on the values of six wool traits of economic importance.

Chapter 2

Review of Literature

2.1 The Romney Breed

The Romney sheep breed came originally from the Romney Marshes in Kent, England. It is considered to be a tough breed and is able to withstand footrot (Emery et al, 1984). It is therefore well suited to higher rainfall areas of New Zealand. Close to 50% of New Zealand's sheep are Romneys (Beef and Lamb NZ, 2017). It is typically used for the production of meat and wool, with the latter's characteristics summarised in table 2. Romney wool is used for the production of carpets, blankets, heavy woollen clothing, furnishing fabrics and handknitting yarn. Fleeces under 33 micron can be used in knitwear products (Fleming, 2003).

Table 2 Typical Romney values for important wool production parameters (Meadows, 2008).

Trait	Typical measurement
Mean fibre diameter	33-40 μ
Greasy fleece weight	4.5-6kg
Staple length	125-175mm
Secondary : primary follicles	5.5
Follicle density	22 follicles/mm ²

2.2 Wool quality traits of interest

Traits selected for improvement by breeding need to be economically important, heritable, and measurable. The use of objective measurement allows price signals to be clearly communicated to the wool production sector, which can then respond with confidence (Binnie et al, 1986). Traits can be desirable or non-desirable, depending on the system the wool will be processed through, and its intended end-use (Wickham, 1982).

2.2.1 Objective measurement of wool

Several techniques have been used to objectively assess wool traits. The development of new techniques has been driven by wool producing countries for the purpose of precisely describing their wool to underpin its value in the market. This has led to the adoption of a standardized certification process, primarily administered by the International Wool Textile Organisation (IWTO) (Baxter, 1996).

Not all wool traits have standardized tests prescribed for them, and some traits can be measured by more than one test (IWTO, 2015). For example, the projection microscope method for measuring

MFD involves manually measuring the width of at least 600 fibre snippets. The airflow method blows air at a fixed pressure through 2.5g of wool compressed into a fixed volume. The rate of airflow is proportional to the surface area of the fibres. By assuming that the cross-sections of the wool fibres are circular, the fibre diameter can be calculated. Therefore high percentages of deformed (i.e medullated) fibres affect the accuracy of airflow measurements (Scobie et al, 1994). The Sirolan Laserscan and Optical Fibre Diameter Analyser (OFDA) are both automated microscopy instruments. They work in a similar way to projection microscopy, and measure at least 1000 and 2000 places respectively from two millimetre fibre snippets (SGS Wool Testing Services, 2014). There are several generations of OFDA machines, with OFDA100 being the first. It was solely a laboratory-based instrument, and has been superseded by OFDA2000, which can be used on-farm (SGS Wool Testing Services, 2014).

The data used in this dissertation was collected using the Fibrescan wool measurement system. This is a novel development in the wool testing industry that uses automated microscopy to rapidly and accurately assess a range of fibre characteristics within a wool sample. The capabilities of Fibrescan are compared to those of existing wool measurement techniques in table 3. Fibrescan uses telecentric lenses which increases tolerance for measuring out-of-focus fibres. Wool samples are measured whole, as opposed to the snippets measured by OFDA and Laserscan. Measuring whole samples allows measurement of staple length and increases the number of readings for, and hence accuracy of, mean curvature measurements. Fibrescan takes 3-400,000 reads from a single sample, resulting in improved accuracy compared to Laserscan and OFDA (D. Morrison, pers. comm.) Fibrescan can measure medullation when Laserscan cannot. Fibrescan always assesses greasy wool, and while OFDA2000 and Laserscan can, they are primarily designed to assess clean wool (SGS Wool Testing, 2011e; NZWTA, n.d).

Table 3 Comparison of wool measurements performed by wool testing systems.

Traits measured	Fibrescan	Laserscan	OFDA2000	Airflow	Projection Microscope
MFD	✓	✓	✓	✓	✓
CVMFD	✓	✓	✓		✓
Coarse edge	✓	✓	✓		✓
Medullation	✓		✓		✓
Staple length	✓				
Mean curvature	✓	✓	✓		✓

2.2.2 Mean fibre diameter

The term 'fibre diameter' describes the average width of a cross section of a wool fibre. It is most commonly expressed in micrometers (μm), also known as microns. Finer fibres facilitate the spinning of finer yarns, which can be incorporated into softer, lighter fabrics with better handle and drape. Mean fibre diameter (MFD) is influenced by the secondary to primary follicle ratio (S:P ratio). The S:P ratio is genetically and nutritionally controlled, and varies between sheep breeds (Rogers, 2006). Purvis et al (1997) showed S:P ratios to be negatively correlated with fibre diameter.

A single fibre has variation in diameter along its own length. This is caused by a variety of physiological and environmental factors, including disease, nutrition, pregnancy and lactation. Significant reductions in MFD are undesirable, because they cause weak points in the fibre that can cause fleece tenderness (Bigham et al, 1983). Tender fleeces break during processing, and so yield shorter fibres than sound fleeces.

Sound wool from a single mob would have an MFD range of $\pm 10 \mu\text{m}$ from the mean. Within a staple, the range is $\pm 8 \mu\text{m}$. Therefore, most of the MFD variability within a flock occurs within a staple (Cottle, 2010). Craven et al (2009) found that MFD differed an average of 2.4 micron between 17 sampling sites on a single sheep. MFD tends to be lesser on anterior and ventral regions, and greater on posterior and dorsal regions (Henderson et al, 1960; Sumner et al, 1973).

MFD was traditionally measured by the airflow or projection microscope methods. The projection microscope method is still used for reference. MFD measurement is available in New Zealand by OFDA and Laserscan (SGS Wool Testing Services, 2011d), but IWTO-28 prescribes the airflow method for wool certification (IWTO, 2015).

2.2.3 Standard deviation and coefficient of variance of mean fibre diameter

Standard deviation (SD) is used as a measure of the variability of the MFD. However, it increases as MFD increases. For this reason, variability is usually given as the coefficient of variation of mean fibre diameter (CVMFD), which remains nearly constant across the range of fibre diameters seen in sheep (Baxter et al, 1997). The CVMFD is the SD divided by the mean, often expressed as a percentage. A single farm's values are typically 20 to 30%. A higher CVMFD affects spinning performance, causes irregularity in yarns and results in stiffer textiles (Cottle, 2010).

2.2.4 Staple length

A wool staple is a naturally formed cluster of wool fibres. Staple length is secondary to MFD in determining the use and value of wool. Disincentives may be applied to discourage short staple lengths.

Staple length is measured in millimetres, and is used as a proxy measurement for greasy wool fibre length. It is highly correlated with hauteur. Hauteur is the mean fibre length in the wool top. Wool top is the ready to be spun product of the worsted wool processing system. Carding is one of the steps in the top-making process. Carding breaks up wool staples and aligns the fibres in parallel. The length after carding is a significant determinant of end-use, price and processing performance of crossbred wool (Orwin et al, 1988). Carding is also a key step in the woolen processing system. Therefore, staple length is an important production parameter for both wool processing systems.

Staple length is mainly determined by the length of time between shearings. It is also affected by genetics and nutrition. Longer staple lengths are only desirable to a point. Most methods of wool processing require all fibres to be under 150mm (Scobie et al, 2015).

Rodriguez Iglesias et al (2013) found variation in staple length between staples on an individual sheep outweighed variation in staple length between sheep when studying Corriedale ewes. IWTO-30 prescribes use of an Automatic Tester of Length and Strength (ATLAS) instrument for staple length measurement (IWTO, 2015).

2.2.5 Crimp/mean curvature

Mean curvature is closely related to crimp. Crimp is the waviness of the wool fibres. Crimp is negatively related to MFD and positively related to bulk. Bulk refers to the ability of wool to occupy space, and is expressed as the volume occupied by a given mass of wool (SGS Wool Testing Services, 2011c).

Mean curvature is the measurement of how much a fibre twists in a given length. It is measured in degrees per millimeter ($^{\circ}/\text{mm}$). Values might exceed $100^{\circ}/\text{mm}$ for fine Merino wools, and be less than $40^{\circ}/\text{mm}$ for coarse wool sheep (SGS Wool Testing Services, 2011a).

Crimp has a major impact on processing performance (Edmunds, 1997). The optimal amount of crimp differs with the end-use of the wool. Higher crimp wools tangle less during scouring and have lower wastage via nops (tangled balls of wool), but have higher noil (short fibres removed during combing),

produce more irregular yarns, and are stiffer than lower crimp wools (Botha et al, 2010). Low crimp wools are easier to spin, whereas higher crimp wools are less inclined to pill (Smith et al, 2005).

It has been suggested that increased crimp results in fabrics which have better 'memory', are more elastic and are less prone to creasing (Holt, 2006; D. Morrison pers. comm.).

Wool bulk is a characteristic which significantly affects the end-use performance of wool (Dick et al, 1996). It is strongly positively associated with mean curvature via the latter's effect on fibre crimp conformation (Sumner et al, 1993; Stobart et al, 1991). Higher bulk wool is desirable for fabric and carpet manufacture (Bigham et al, 1984).

Both OFDA and Laserscan can be used to measure mean curvature (Edmunds, 1997).

2.2.6 Coarse edge

Coarse edge, also known as prickly factor, or inversely comfort factor, is the percentage of fibres over a certain MFD threshold (typically 30 microns). It is directly related to the CVMFD. It is important for determining suitability of wool for garments to be worn against the skin (Naylor, 1992). Wool prickly is an uncomfortable itching sensation that some wool garments cause. Naylor (2010) showed that the force a fibre can exert before buckling is dependent on its diameter. Fibres over 30 micron contribute more to wool prickly than fibres under 30 micron (SGS Wool Testing Services, 2011d). If the coarse edge value is less than 5%, wool prickly is reduced enough to not be noticed by most people under most conditions (Garnsworthy et al, 1985). Temperature and level of activity can also affect prickly (Naylor et al, 2014; Wang et al 2003).

It has been suggested that medullated fibres increase wool prickly due to their non-spherical shape. The thin longitudinal edge of some medullated fibres may cause skin irritation by 'slicing', rather than 'stabbing' the skin (D. Morrison, pers. comm.).

Most Romney fibres are over 30 micron. Coarse edge is defined in this context as the percentage of fibres 10 or more micron greater than the mean.

2.2.7 Medullation

Medullated fibres are poorly formed with a continuous or fragmented hollow core. They tend to be coarser than non-medullated fibres, and as such medullation is an undesirable trait in a breeding

program aiming for smaller MFD. The proportion of medullated fibres in a fleece tends to increase as the CVMFD increases. There is a strong positive correlation between medullation and fibre diameter (Ross, 1990). Medullated fibres negatively affect spinning performance (SGS Wool testing Services, 2011b), and the hollow core results in medullated fibres showing a lighter shade than non-medullated fibres after dyeing (Gupta et al, 1987).

Goot (1945) reported variation between percentage of medullated fibres on the hind quarters (4.5-7.5%), side (3.0-5.6%) and forequarter (2.4-2.9%) of Romney sheep.

Medullation was traditionally assessed by the projection microscope method, which was slow and relatively inaccurate. Two other techniques, the WRONZ Medullameter and Near Infra-red Reflectance Analysis, are not commonly used (SGS Wool Testing Services, 2014). OFDA can be modified to measure medullation. It relies on the opacity of medullated fibres compared to non-medullated fibres (Lee, 1999). IWTO accepts measurement of medullation by both projection microscope and OFDA (IWTO, 2015).

2.3 Heritabilities and correlations of wool quality traits

2.3.1 Heritability of MFD

Table 4 Estimates of heritability of MFD in dual purpose sheep

Age (months)	h^2	Breed	Reference
12	0.56 ± 0.10	Corriedale	Brash et al 1994a
16	0.62 ± 0.14	Corriedale	Brash et al 1994b
14	0.52 ± 0.07	Corriedale	Benavides et al 1998
12	0.55 ± 0.05	Romney	Wuliji et al 1998

MFD is a highly heritable trait. Table 4 compiles estimates of MFD heritability in dual purpose sheep. Turner et al (1970) showed that selection of Merino ewes for low and high MFD resulted in significant deviations from the control line (Low: -13.6%; High: 13.4%). Additionally, there was a positive genetic correlation with fleece weight and no significant change to yield or staple length. This demonstrates the viability of making rapid genetic gains when selecting sheep for reduced MFD.

Safari et al (2003) provided data which showed a weak negative trend in correlation between MFD and CVMFD in Merinos. Therefore, a selection for reduced MFD will result in a slight increase in CVMFD.

Wuliji et al (1998) showed that MFD and staple length are positively genotypically correlated (0.37 ± 0.09) in Romneys.

Table 5 Estimates of correlations between greasy fleece weight (GFW) and MFD

GFW age (months)	MFD age (months)	r_g	r_p	Breed	Reference
12	12	0.21 ± 0.15	0.37 ± 0.02	Corriedale	Brash et al 1994a
12	16	0.23 ± 0.27	0.29 ± 0.04	Corriedale	Brash et al 1994a
12	12	0.42 ± 0.25	0.31 ± 0.03	Coopworth	Brash et al 1994b
12	12	0.38 ± 0.08	0.48 ± 0.02	Romney	Wuliji et al 1998

Greasy fleece weight and fibre diameter are positively correlated in dual purpose sheep (table 5).

Therefore, decreasing MFD will decrease GFW. Inversely, increasing GFW increases MFD. This means that focusing on wool quantity actively erodes wool quality.

Table 6 Estimates of correlations between liveweight (LW) and MFD

LW age (months)	MFD age (months)	r_g	r_p	Breed	Reference
4	12	0.23 ± 0.17	0.14 ± 0.02	Romney	Wuliji et al 1998
12	12	0.27 ± 0.08	0.34 ± 0.02	Romney	Wuliji et al 1998

Table 6 shows positive correlation values between liveweight (LW) and MFD. This implies that a reduction in MFD will cause a reduction in LW. Smaller ewes have higher reproductive efficiencies due to lower maintenance requirements and so are desirable in a breeding flock (Large, 1970).

However, a ewe can be too small. One reason for this is that smaller ewes have an increased likelihood of fetomaternal disproportion, resulting in dystocia (Thomas, 1990).

2.3.2 Heritability of staple length

Table 7 Estimates of heritability of staple length in dual purpose sheep

Age (months)	h^2	Breed	Reference
12	0.4 ± 0.06	Romney	Wuliji et al 1998
Adult	0.47	Columbia	Bromley et al 2000
Adult	0.54	Polypay	Bromley et al 2000
Adult	0.36	Rambouillet	Bromley et al 2000
Adult	0.53	Targhee	Bromley et al 2000
12	0.55 ± 0.04	Columbia	Hanford et al 2002

Staple length is a highly heritable trait for dual purpose sheep (table 7).

Wuliji et al (1998) showed that greasy fleece weight (GFW) and staple length are strongly correlated (0.5 ± 0.09) in Romneys.

2.3.3 Heritability of CVMFD

Wuliji et al (2001) studied ultrafine Merinos and found the CVMFD to be 0.60. Safari et al (2003) provided values which show an average CVMFD heritability of 0.52 in Merinos. The same Merino data showed a weak negative correlation between GFW and CVMFD.

Table 8 shows that CVMFD is extremely strongly correlated between the age of 10 and 16 months in Merino sheep.

Table 8 Estimate of correlations between ages for CVMFD

Age (months)	Age (months)	r_g	Breed	Reference
10	16	0.92	Merino	Ponzoni et al 1995
10	16	0.94 ± 0.04	Merino	Brash et al 1997
10	16	0.95 ± 0.03	Merino	Hill 2001

2.3.4 Heritability of crimp/mean curvature

Safari et al (2003) provided values which show an average crimp frequency heritability of 0.42 in Merinos. Table 9 shows that estimates of the heritability of mean curvature in Merino sheep lie between 0.4 and 0.5. Taylor et al (1999) showed that MFD and mean curvature are negatively correlated (-0.2 ± 0.08) in Merino sheep.

Table 9 Estimates of heritability of mean curvature

Age (months)	h^2	Breed	Reference
16	0.39 ± 0.07	Merino	Taylor et al 1999
12	0.47 ± 0.15	Merino	Brown et al 2002
18	0.40 ± 0.11	Merino	Brown et al 2002

Sumner et al (2001) found that Romney mean curvature decreased linearly from $50^\circ/\text{mm}$ at one year of age to $30^\circ/\text{mm}$ at 5 years of age.

2.3.5 Heritability of medullation

Rae (1964) estimated medullation to have a heritability of 0.63 in Romney hoggets.

2.3.6 Heritability of fibre diameter stability

Micron blowout, also known as diameter stability, is the tendency of MFD to increase in some sheep as they mature, at a more rapid rate than the average of the group to which they belong. Purvis et al (1997) found the heritability of fibre diameter stability to be 0.19 in Merino sheep. Atkins (1996) reported a diameter increase of 0.2 to 0.3 microns per year in Merino breeding ewes. It is suggested that this figure would be larger were it not for the stresses of bearing and rearing lambs. Turner et al (1968) also reported on MFD changes in Merino ewes (table 10). These show a slight increase over what would be considered the normal productive lifespan of a ewe. It has been shown that Romney ewes with 32 micron fleeces at one year of age, or 29 micron fleeces at lambing, increase to a peak of 38 micron at 3 years of age and decrease thereafter (Sumner et al, 2001; Sumner et al, 1997). This must be accounted for when selecting replacement ewes in a breeding scheme.

Table 10 **Change in MFD with age in Merino ewes**

Age (years)	Δ MFD
2.5	0
3.5	1.3
4.5	1.79
5.5	2.12
6.5	2.66
7.5	1.35
8.5	0.1
9.5	-1.21
10.5	-4.44

Table 11 Estimate of correlations between ages for MFD

Age (months)	Age (months)	r_g	Breed	Reference
16	28	0.96	Merino	Hickson et al 1994
16	40	0.91	Merino	Hickson et al 1994
16	52	0.82	Merino	Hickson et al 1994
16	64	0.87	Merino	Hickson et al 1994
10	46	0.91	Merino	Hickson et al 1995
10	46	0.89 ± 0.04	Merino	Brash et al 1997
15	2yr	0.93 ± 0.02	Merino	Coelli et al 1998
15	3yr	0.92 ± 0.02	Merino	Coelli et al 1998
15	4yr	0.88 ± 0.02	Merino	Coelli et al 1998
15	5yr	0.83 ± 0.03	Merino	Coelli et al 1998
15	6yr	0.80 ± 0.03	Merino	Coelli et al 1998
10	16	0.95 ± 0.02	Merino	Hill 2001

Table 11 shows that, for merino sheep, MFD genotypic correlations are extremely high between a range of age groups. The results of Coelli et al (1998) show that these correlations reduce between 3 and 6 years of age, but nonetheless remain comparatively high. These results imply that age has a negligible effect on MFD heritability.

Chapter 3

Materials and Methods

3.1 Methods

This study used 437 Romney ewes born in spring, 2015. The ewes were the first generation progeny of a selective breeding program aiming to reduce MFD and increase fibre curvature. They were run as part of a commercial flock on 'The Doone', a hill country farm in North Canterbury, New Zealand. On 5/10/16 and 2/8/17, prior to being shorn, a wool staple was cut from each ewe. The wool staples were taken from the ewe's midside, one hands span down from the spine over the last rib. The staple samples were dried before being individually analysed with a Pastoral Measurements Ltd FibreScan automated microscopy machine. From this, values for the following traits were obtained: MFD (μm), standard deviation of MFD, coefficient of variation of MFD, staple length (mm), mean curvature ($^{\circ}/\text{mm}$), coarse edge (% $10\mu\text{m} > \text{mean}$) and medullation %.

The 437 ewes all had paired data, allowing between year comparisons. Ewes from sires with fewer than 4 paired-data progeny were disregarded for the sire comparisons, as were ewes without recorded sires. This screening left 181 ewes for use in the sire comparisons.

3.2 Statistical Analysis

IBM SPSS Statistics 22 was used for all statistical analysis. The data set for each trait was assessed for normality of distribution. A Levene's test was used to check homogeneity of variances. Mean differences between years were calculated for each trait. A paired samples t-test was used to calculate correlations within traits across ages at sampling. Two-way ANOVAs were conducted to establish whether there was a significant effect of sire, age at sampling, or sire*age at sampling on MFD, CVMFD, staple length, mean curvature and coarse edge. A McNemar's test was carried out to establish whether the proportion of medullated ewes changed significantly between the two years.

Chapter 4

Results

4.1 Effect of sire and age at sampling on wool traits

Table 12 *P*-values showing significance of sire, age at sampling and sire*age at sampling on traits

	MFD	CV	Staple length	Mean curve	Coarse Edge
Sire	<0.001	0.004	<0.001	<0.001	<0.001
Age at sampling	<0.001	0.369	<0.001	<0.001	<0.001
Interaction	0.911	0.265	0.695	0.923	0.695

Table 13 Mean trait values for age groups and mean differences between age groups. Units shown in table: MFD: micron, CV: %, staple length: mm, mean curve: \hat{A}°/mm , coarse edge: % 10 micron >mean, medullation %: average amount of medullation within a fleece.

	MFD	CV	Staple length	Mean curve	Coarse edge	Medullation %
Hoggets	31.9	22.8	87.7	71.3	8.8	0.5
2ths	37.4	22.6	110.1	56.1	10.5	0.3
Mean difference	5.5	-0.2	22.4	-15.2	1.8	-0.2

Table 12 shows that sire significantly affected MFD, CVMFD, staple length, mean curvature, and coarse edge. This was expected, due to the high heritabilities of all five traits, and confirms that not all the rams are of equal genetic merit.

The age of the ewes at sampling significantly affected MFD, staple length, mean curvature and coarse edge. MFD is known to increase for the first three years of life in Romney sheep, and mean curve has been shown to decrease over the same time frame (Sumner et al, 2001). Table 13 shows that the change in MFD and mean curvature in this case was also a respective increase/decrease. MFD increased 5.5 micron on average. Mean curvature decreased 15.2 \hat{A}°/mm . The significant effect of age at sampling on staple length is meaningless, as the ewes were sampled at different times relative to shearing each year. Age at sampling did not have a significant effect on CVMFD. This shows that variation in MFD did not increase with age. Coarse edge, which is closely related to CVMFD, did significantly increase.

The medullation data was non-parametric (figure 3) and was not analysed in the ANOVA. Average medullation percentage across the flock decreased 40% across age at sampling.

No significant interactions between sire and age at sampling were observed. Therefore, similar amounts of change were seen in the wool traits of all progeny groups as they matured.

All traits were positively correlated between age groups (figure 2). Mean curvature, MFD and coarse edge were all strongly correlated. CVMFD was weakly correlated. Therefore the hoggets with high mean curvature, low MFD and low coarse edge will be the same animals displaying those fleece characteristics as two toothed. This result agrees with the lack of a significant interaction between sire and age at sampling.

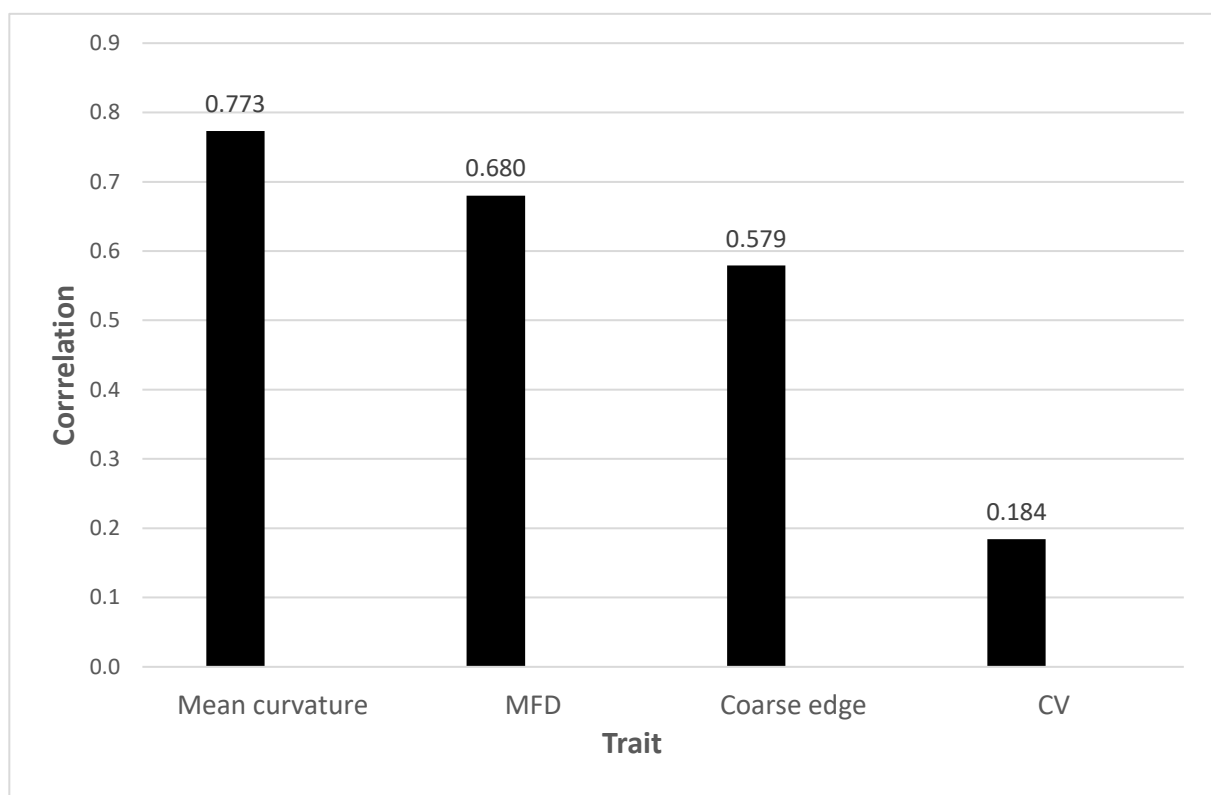


Figure 2 Correlations of traits between age groups

4.2 Effect of age group on proportion of medullated ewes

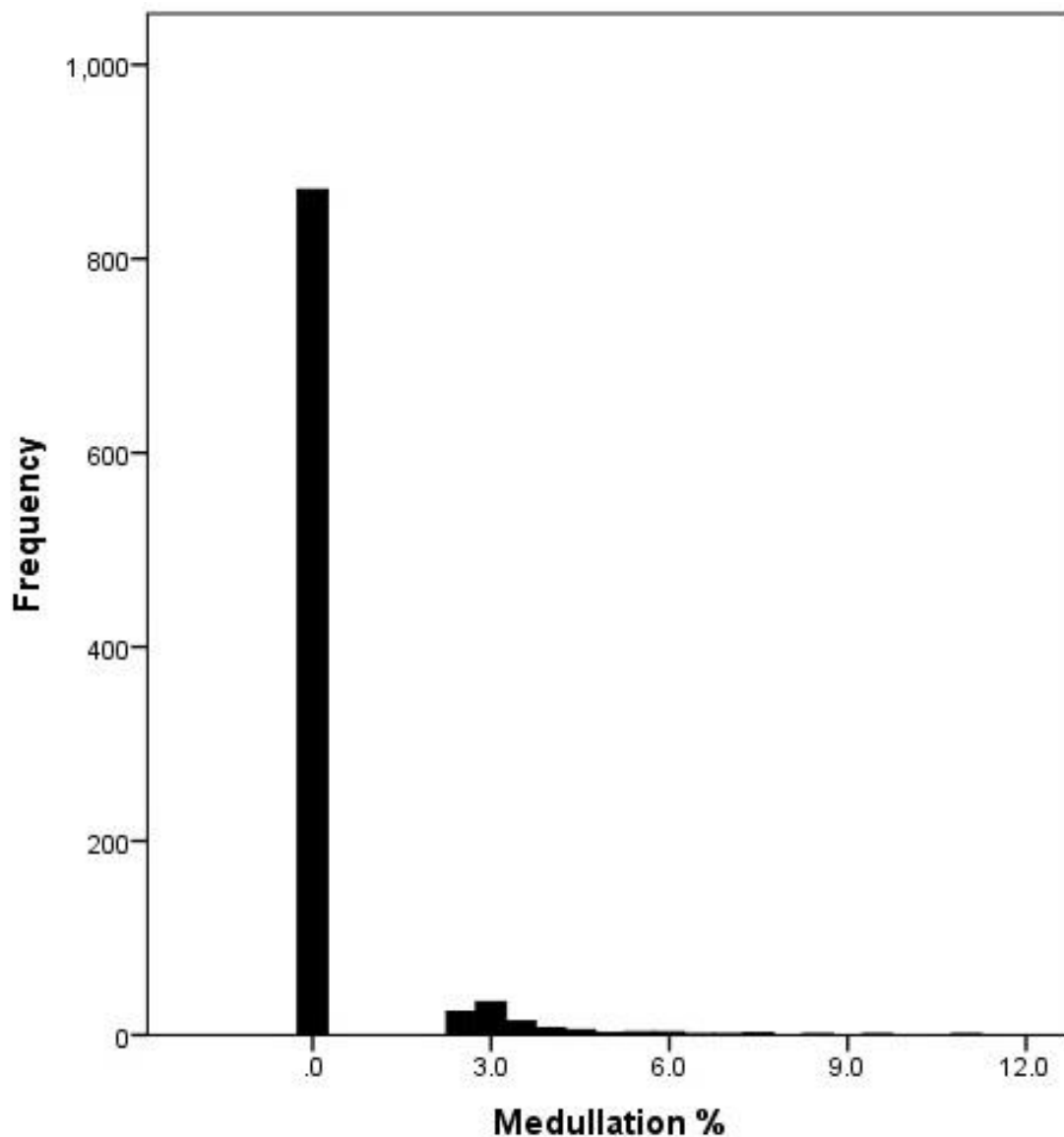


Figure 3 Histogram showing distribution of within fleece medullation percentage

Medullation was the only trait that was not normally distributed. Figure 3 shows that the majority of ewes never showed any medullation. The mean value for ewes that did show medullation was 4.24%.

Medullation is an undesirable fleece characteristic in the context of this breeding objective. Because of this it was categorised as dichotomous data where ewes either did or did not have medullated fleeces. This allowed the difference in proportion of ewes showing medullation per year to be analysed with a McNemar's test ($p < 0.001$).

Table 14 shows that the 371 ewes never showed any medullation in their fleece samples, compared to 22 ewes that showed medullation at both sampling times. Six ewes showed no medullation as hoggets but did show medullation as two teeth, and 38 ewes showed medullation as hoggets but did not show it as two teeth.

Table 14 **Distribution of animals with presence or absence of medullation as hoggets (Med(H)) and as two teeth (Med(2th)).**

		Med (2th)		Total
		Absent	Present	
Med (H)	Absent	371	6	377
	Present	38	22	60
Total		409	28	437

Birth date was recorded for 185 of the 437 ewes used in this analysis. There was a seven week difference between the oldest and the youngest lambs. There were not enough medullated lambs with birth date data to determine if single occurrence/ repeat occurrence of medullation was affected by birth date.

Overall, fewer animals showed medullation as two teeth (6.4%) than as hoggets (13.7%). The majority of animals which will show medullation at some point already do so as hoggets. The majority of those animals do not show medullation as two teeth. The combination of high heritability (Rae, 1964) and low phenotypic display in the flock mean a zero-medullation flock is an achievable target.

4.3 Ranking of sires for wool traits

Table 15 Sire rankings alongside mean progeny values (averaged across age at sampling).

*Medullation= % of ram's progeny which showed medullation as two tooth.

Sire	Mean progeny values and ram ranks											
	MFD		CV		Staple length		Mean curve		Coarse Edge		Medullation*	
Gleneyre 308	33.33	1	22.94	10	93.25	12	61.26	9	9.30	6	0.00	1
Doughboy 32	33.80	2	22.59	6	89.13	14	62.63	7	8.85	4	0.00	1
Doughboy 227	33.93	3	22.32	4	99.81	5	62.17	8	8.63	2	0.06	6
Doughboy 64.14	34.24	4	22.44	5	99.80	6	60.97	10	9.16	5	0.10	10
Doughboy 227.13	34.45	5	22.98	11	97.75	9	65.55	3	9.99	7	0.08	8
Waimai 337.12	34.63	6	20.14	1	99.63	7	65.05	4	6.87	1	0.25	14
Doughboy 32.13	34.78	7	23.82	13	95.00	10	64.30	5	11.28	11	0.00	1
Doughboy 235.12	35.07	8	24.23	14	97.88	8	64.12	6	11.36	13	0.13	11
Waimai 337	35.49	9	21.74	2	93.50	11	66.29	2	8.74	3	0.17	13
Te Ohu 6314	36.18	10	22.29	3	92.94	13	67.73	1	10.36	8	0.00	1
Anui 409	36.67	11	23.07	12	105.12	1	58.24	14	11.29	12	0.08	7
Kikitangeo 847	36.77	12	22.88	9	103.88	4	60.93	11	10.61	10	0.13	11
Gleneyre 905	36.94	13	22.75	8	104.14	3	60.04	13	10.54	9	0.00	1
Supreme 461	37.18	14	22.69	7	104.33	2	60.31	12	11.39	14	0.10	9

Table 12 established that sire has a significant effect on MFD, CVMFD, staple length, mean curvature, and coarse edge. Table 15 summarises which sire performed best for each of those traits, as well as for medullation, which was not analysed. Medullation is treated here as a dichotomous variable- the sires are ranked based on how many of their progeny showed no medullation as two tooth.

Medullated hoggets were disregarded because the effect of birth date on the loss of medullated lamb coats could not be accounted for. Staple length can be considered here despite the differences in shearing date between the years, because all ewes were shorn and sampled on the same dates as each other in a given year. This means that sire effects can be distinguished. The ability to produce longer staple lengths has been ranked positively. Although fibres can be too long for processing, these ewes are not close to the 150mm cutoff, and fast wool growing ewes can be managed with a more frequent shearing regime.

The table shows that Gleneyre 308 sired the ewes with the lowest group average MFD (33.3 micron). Several rams sired ewes which showed no medullation as two tooth. The progeny of Waimai 337.12 had the lowest CVMFD (20.14%), and the lowest coarse edge (6.87%). It is unsurprising that a single ram ranks top for both these traits given their interconnectedness. Anui 409 sired the group with the longest staple length (105.12mm), but scored badly for MFD, CVMFD, mean curve and coarse edge. This is explained by staple length's strong positive correlation with MFD, which is in turn negatively correlated with mean curvature. Despite the negative correlation between MFD and fibre curvature, Te Ohu 6314, who ranked highest for mean curvature, ranked 10th for MFD. Significant differences typically existed between the top-ranked and bottom ranked sires.

Chapter 5

Discussion

5.1 Context

Higher prices for sheep meat compared to strong wool has resulted in dual purpose sheep breeding objectives aligning with meat production (Craven et al, 2009). The consequent lack of focus on wool breeding has resulted in reduction of the quality and value of strong wool. The value of wool can be increased by selective breeding focused on wool traits that are valuable to the processor and the end user (Binnie et al, 1986). This study sought to determine the effects of sire and age on six wool traits of economic importance.

5.2 Effect of age on wool traits

Significant differences were seen in all wool traits, other than CVMFD, as the flock matured from hoggets to two tooth.

5.2.1 MFD

MFD increased 5.5 micron on average. This agrees with the literature, which indicates that MFD changes over the lifetime of a sheep. Sumner et al (2001) observed a similar amount of change in Romney and Romney cross ewes measured as hoggets and again as two tooth. The dynamic nature of MFD over time affects the accuracy with which ewes can be selected for culling or mating at a young age. Andrews et al (1997) showed that adult MFD can be predicted from hogget MFD with an accuracy of 0.87. This is higher than the correlation value of 0.68 reported in the present study. Nonetheless, the correlation between ages for MFD is high enough to indicate that ewes can be selected based on MFD measurements before maturity, as was also stated by Sumner et al (2001). However, the combined dataset derived from studies like the present one is currently small. This affects the accuracy with which such predictions can be made for the wide range of phenotypes and environments seen in the farming of Romney sheep. Marker-assisted selection may provide an alternative method for choosing cull and replacement sheep. Gong et al (2016) noted that there is ongoing work associating variation in keratin-associated protein (KAP) genes with variation in wool traits. One of these studies identified a 57 base pair deletion in the *KRTAP6-1* gene as being associated with higher MFD wool in Southdown x Merino lambs (Zhou et al, 2015). This work is made more difficult by the high linkage between, and polymorphic nature of, KAP genes (Gong et al, 2016).

The mechanism by which MFD increases with age was laid out by McGregor et al (2016). Wool fibres grow from wool follicles. New follicles do not appear after about 4 months of age in sheep. Figure 4 shows that MFD decreases in a curvilinear manner as wool follicle density increases (Scobie et al, 2000). This happens because the skin surface area of an animal increases as it grows, but the number of follicles does not. Lower follicle densities allow follicle bulb dimensions to increase (Hynd, 1994), consequently increasing fibre diameter (McGregor et al, 2016). The peak follicle density of Romney lambs is roughly a quarter of that of Merino lambs (Hocking Edwards et al, 1994). Assuming follicle densities change by a similar amount in all breeds as they grow, this explains why similar amounts of growth over similar periods of time result in much larger MFD changes in strong wool breeds than fine wool breeds. Measurement of follicle density in immature sheep may provide a means of estimating peak MFD (Hynd et al, 1996).

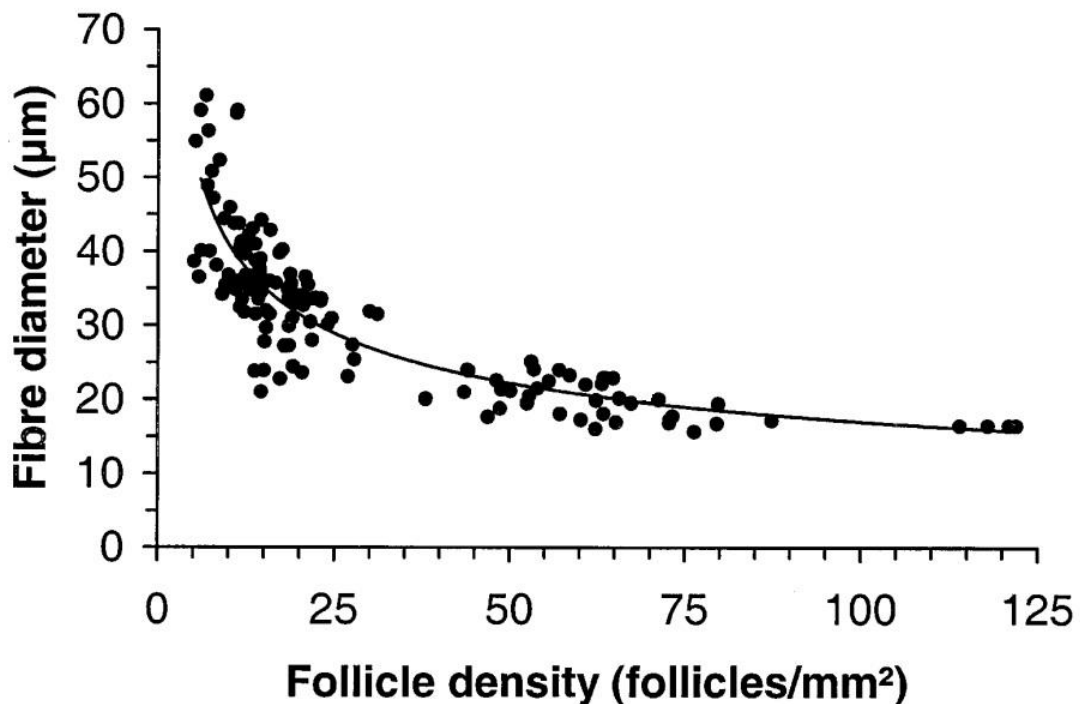


Figure 4 Relationship between fibre diameter and follicle density (Scobie et al, 2000).

5.2.2 Mean curvature

Mean curvature decreased from 71.3 to 56.1 $^{\circ}$ /mm as the ewes matured. Sumner et al (2001) found that Romney, Romney x Dorset and Romney x Texel ewes also exhibited a decrease of approximately 15 $^{\circ}$ /mm as they matured from hoggets to two teeth, regardless of their initial mean curvature value. Fibre curvature may be caused by bilateral differentiation of cortical cells on the outside and inside of the fibre curve (Plowman et al, 2007). As shown above, follicle density decreases with age.

Nay et al (1969) found that follicle density is negatively related to crimps per unit length in Merino ewes. These findings run contrary to the results of the present study, assuming that follicle density has in fact decreased in these ewes. This may be attributable to differences in crimp formation between Romney and Merino sheep. Mean curvature is also negatively correlated with follicle depth (Nay et al, 1969). Follicle depth, measured as the vertical distance of the follicle bulb from the surface of the skin, can decrease with the disappearance of tissue such as fat, due to the skin becoming thinner (Nay et al, 1972). The rate of subcutaneous fat deposition increases in ruminants as they mature (Owens et al, 1993). Dick et al (1996) found that follicle depth in Perendale lambs increased in a curvilinear manner up to 50 weeks of age, with no data available beyond that time. The hoggets in this experiment were sampled around 54 weeks of age. Therefore, an alternative reason for the decrease in mean curvature with age may be a continued increase in follicle depth beyond 50 weeks of age, possibly caused by an increase in fat depth on the ewes.

5.2.3 Coarse edge and CVMFD

Two toothed had significantly higher coarse edge percentages than hoggets. This is unsurprising, as coarse edge is correlated with MFD, and so the increase in coarse edge could be predicted on the basis of the increase in MFD (Baxter et al, 1997). Coarse edge is also correlated with CVMFD (Baxter et al, 1997). CVMFD did not significantly increase as it was expected to. No explanation has been found for why this occurred.

5.2.4 Medullation

The average amount of medullated fibre in the flock decreased 40% as the ewes matured. The results show that the majority of this change arose from medullated hoggets losing all medullation as they aged. Grandstaff et al (1944) observed a drop from 15% medullation at 28 days old to 2.4% medullation at 84 days old in Navajo lambs. Similar drops were recorded between two and five months of age in Rambouillet, Targhee, Corriedale and Columbia breeds (Pohle et al, 1945). This drop has implications for the accuracy with which replacement and cull animals can be selected. A greater understanding of why this change in medullation occurs would allow increased selection accuracy.

Pohle et al (1945) noted extremely coarse, medullated lamb hairs were present alongside 'normal' medullated wool fibres (figure 5). Fibrescan cannot differentiate between these types of fibre. Therefore it is possible that the shedding of lamb hairs as described by Grandstaff et al (1944) explains the ewes which lost all medullation, while the constant presence of 'true' medullated fibres explains the 22 consistently medullated ewes. The seven week difference in recorded birth dates

may mean that there were also other lambs that showed medullation. If these lambs were older, or matured more rapidly, they may have lost their medullated birthcoats completely by the first sampling date. Too few lambs had recorded birth dates to perform analysis to prove this. Such an effect could be demonstrated in future experiments by either recording the birth dates of more lambs or sampling wool at an additional, earlier, date.

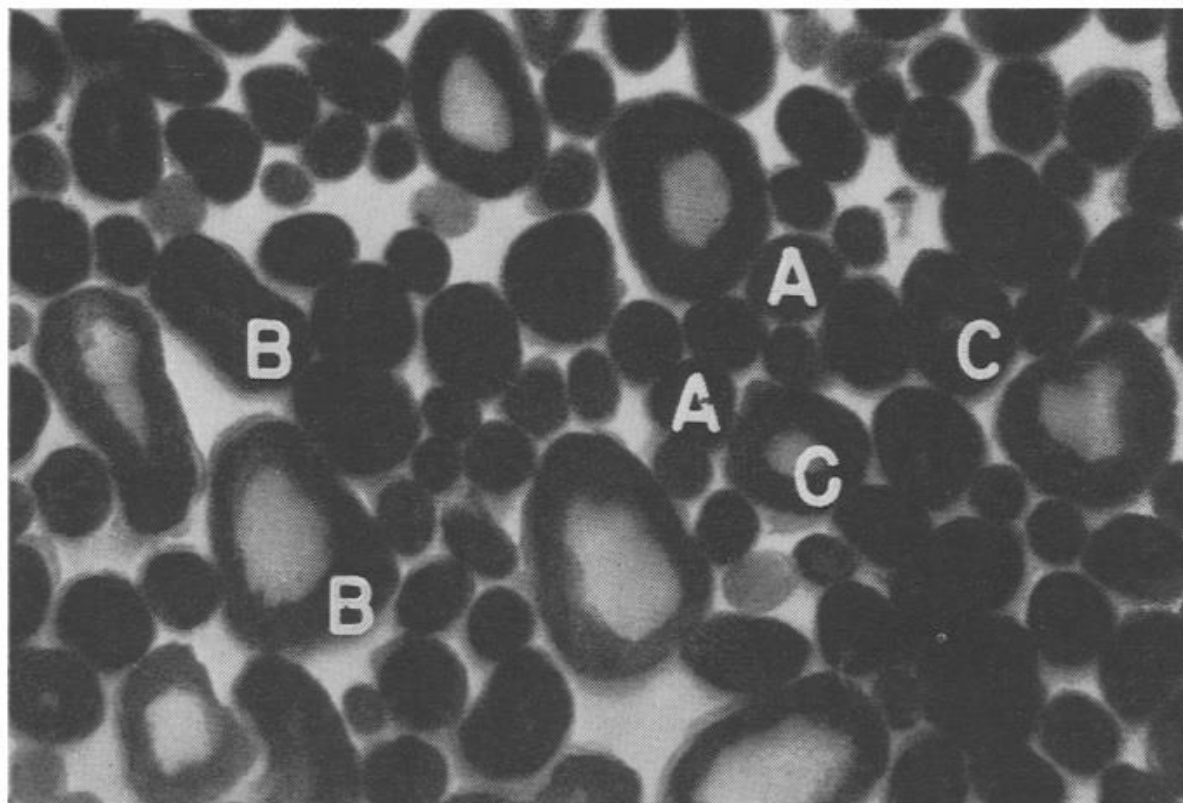


Figure 5 Cross section of fibres collected at two months of age from a 'hairy' Rambouillet lamb: A: true wool; B: lamb hairs; C: medullated fibres. Reproduced with permission. (Pohle et al, 1945).

The insulative value of wool is derived from its ability to trap air, as air has the lower thermal conductivity (Indu Shekar et al, 2001). The fur of the brushtail possum (*Trichosurus vulpecula*) is 55% warmer than Merino wool (New Zealand Fur Council, 2013), and the majority of possum fur fibres are medullated (Gore et al, 2002). The increased warmth of possum fur has been attributed to this extensive medullation allowing possum fur to trap more air than non-medullated wool (Hassan, 2016). Cold exposure is a cause of death for many neonatal lambs (Haughey, 1991). Thus, there is a strong selection pressure for traits which decrease the cold-induced mortality rate of lambs, and it is possible that the lambs which grow medullated fibres do so as an adaptation to cold. Olivier et al (2009) found that increased hairiness at birth was weakly positively correlated with survival to weaning for Merino lambs in South Africa. Comparing climate data shows that neonatal lambs in South Africa are less likely to experience cold stress than their counterparts in New Zealand, and so it is probable that correlation values based on New Zealand data would be higher. Alexander (1964)

compared lambs with and without hairy birth coats in a climate chamber study, and found the hairy lambs were better at conserving heat. Other studies show that this only affects lamb survival in cold conditions where deaths due to exposure are high (Mullaney, 1966; Obst et al, 1970). Although there is no New Zealand-specific data supporting this, these findings imply that breeding objectives which allow no medullation at all may negatively affect lamb survival.

5.3 Effect of sire on wool traits

Sire significantly affected MFD, CVMFD, staple length, mean curvature and coarse edge. This agrees with the common findings in the literature that these wool traits are moderately to highly heritable. That is because the only effect the rams have on their progeny is a genetic one. Major environmental factors (location, nutrition) were controlled for, and so the ram's genetic effect must be responsible for the large amount of variation within each trait. This in turn confirms that progress in all of these traits can be made via selective breeding.

5.3.1 MFD

There were clear differences between the sires when ranked for MFD. Significant differences existed between each of the top and bottom three rams. Gleneyre 308, Doughboy 32, and Doughboy 227 produced ewes which averaged between 33 and 34 microns across two years. This is very close to the 32 micron mark, below which wool is appropriate for processing into fabrics (Fleming, 2003). There was no interaction between sire and age at sampling for any of the wool traits, including MFD. These rankings then indicate that these three rams produced the finest wool hoggets as well as the finest wool two tooth, rather than exceptionally fine progeny in one year which compensated for mediocre MFD progeny in the other. This is further confirmation that mature MFD can be predicted from hogget fleeces.

5.3.2 Staple length

Sire significantly affected staple length in both hoggets and two tooth. There was a difference in length of 16mm between Anui 409 and Doughboy 32, who were the top and bottom ranked sires for staple length. The sires which ranked top for staple length also ranked bottom for MFD. This observation agrees with the idea that fibre diameter and length being positively correlated (Brown et al, 2005). Staple length is strongly correlated with GFW (Wuliji et al, 1998). Therefore, this finding implies that continued selection for lower MFD will reduce GFW. It also confirms that mainstream

industry maternal indexes, which only rate wool production based on GFW, effectively select for reduced wool quality (SIL, 2017).

5.3.3 Mean curvature

Mean curvature was significantly affected by sire. Significant differences were seen between the top and bottom three rams. The progeny from the top ranked rams exceeded 65 $^{\circ}$ /mm on average, while the progeny of the worst ram averaged 58 $^{\circ}$ /mm. On average, the mean curvature of the ewes was better than previously reported in the literature. Sumner et al (2001) found that Romney mean curvature, averaged between hogget and two tooth Romney ewes, was 45 $^{\circ}$ /mm. Crimp, closely related to mean curvature, is highly heritable (0.42) in Merinos (Safari et al, 2003). Assuming that this implies mean curvature is also highly heritable in Romneys, this means genotype is a major determinant of the mean curvature observed in the flock. The highest mean curvature value reported was 91.9 $^{\circ}$ /mm. This indicates that the genetic potential exists in the combined NZ Romney flock for continued increases in mean curvature values.

5.3.4 Medullation

Any degree of medullation is undesirable in the possible end-uses of improved strong wool. Therefore, in order to breed the optimal wool-producing flock, medullation has to be completely removed. Because medullation a) was non-normally distributed and b) needed to be completely absent, it was logical to analyse it as a dichotomous variable. However, most rams had too few recorded progeny to meet the minimum requirements of a chi-square test. For that reason, no statistical analyses could be performed to determine if there was a significant effect of sire on medullation, either as an overall fleece medullation percentage or as number of lambs medullated. Nonetheless, the sires were ranked based on the number of their progeny which showed medullation as two tooth. The hogget medullation data was disregarded as it may have been affected by birth date. Five of the 14 rams that were compared sired groups of ewes which showed no medullation as two tooth. This confirms that genetic differences are involved in determining medullation, although this study cannot say whether those differences are significant. Future studies could state their results with certainty if more progeny information was available per ram.

A ram is only capable of siring so many lambs in a season, however. The number of progeny could be increased via artificial insemination, or by comparing progeny from multiple age groups. Matching progeny to sires via using ram harnesses to record matings and then matching lambs to ewes in the paddock is an exhaustive process with potential for error. This dataset combined this process with

DNA sampling of lambs in order to improve accuracy. Technologies such as Pedigree Matchmaker utilise RFID tags and in-paddock scanners to match progeny to ewes. Such technology would provide a way of matching progeny in larger lambing mobs or in more extensive farming systems. However, it would require RFID tagging of all lambs and ewes, and does not match rams with ewes.

5.4 Conclusion

A shift in focus away from wool production has led to a decline in strong wool quality and therefore price. Farmers can increase their wool revenue by increasing the quality of wool, thus making it suitable for higher value end-uses. MFD is the key driver of wool price, due to its influence on both wool processing and the quality of the final product. Mean curvature, medullation, CVMFD, staple length and coarse edge are all wool traits that also influence wool value. Data was collected at different ages from Romney ewes sired by different rams. Analysis of this data found that wool tends to decline in quality as ewes mature, but by a constant amount, showing that mature wool traits can be predicted from hogget data within a given environment. Significant differences were observed between rams for MFD, CVMFD, staple length, mean curvature and coarse edge. This confirms previous findings in the literature that these traits are highly heritable, and therefore can be improved via selective breeding.

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